

Future High Energy Neutrino Telescopes

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This talk summarizes the main physics goals and basic methods of telescopes for high energy neutrinos. It reviews the present status of deep underwater telescopes and sketches the ICECUBE project as an example for a cube kilometer detector. It is suggested to develop techniques for radio and acoustic detection hand in hand with big optical arrays. These large arrays should be complemented by medium-size detectors in the Megaton range.

1. Physics and Methods

Whereas MeV neutrino astronomy has been established by the observation of solar neutrinos and neutrinos from supernova SN1987, neutrinos with energies of GeV to PeV which must accompany the production of high energy cosmic rays still await discovery. Detectors underground have turned out to be too small to detect the feeble fluxes of energetic neutrinos from cosmic accelerators. The high energy frontier is being tackled by much larger, expandable arrays constructed in open water or ice. The physics goals of high energy neutrino telescopes have been covered in detail by other talks of this conferences. They include:

- a) Search for neutrinos from cosmic acceleration processes in galactic sources like binary systems or supernova remnants (SNR), or extragalactic sources like active galactic nuclei (AGN) or gamma ray bursters (GRB) [1,2].
- b) Search for ultra high energy neutrinos from topological defects (TD) [3].
- c) Search for neutrinos from the annihilation of Weakly Interacting Massive Particles (WIMPs) [4].
- d) Search for magnetic monopoles.
- e) Investigation of neutrino oscillations, using neutrinos from accelerators, the atmosphere or extraterrestrial neutrinos [5].
- f) Monitoring for MeV neutrinos from supernova bursts in our Galaxy [6].

- g) Cosmic ray physics with atmospheric muons

The telescopes presently under construction detect the Cherenkov light generated by secondary particles produced in neutrino interactions. They are optimized for the detection of muon *tracks* and for energies of a TeV or above, by the following reasons:

- a) The flux of neutrinos from cosmic accelerators is expected to behave like $E_\nu^{-2.0 \div 2.5}$ whereas the spectrum of atmospheric neutrinos above 100 GeV falls like $E_\nu^{-3.7}$, yielding a better signal-to-background ratio at higher energies.
- b) Neutrino cross section and muon range increase with energy. Due to the large muon range, the effective volume of the detectors may considerably exceed their geometrical volume.
- c) The mean angle between muon and neutrino decreases with energy like E^{-2} , with a pointing accuracy of about 1.5° at 1 TeV.
- d) Mainly due to pair production and bremsstrahlung, the energy loss of muons increases with energy. For energies above 1 TeV, this allows to estimate the muon energy from the larger light emission along the track.

There are questions which require a threshold in the range a several GeV or a few tens of GeV, like the study of neutrino oscillations or

the search for neutrinos from WIMP annihilation. Since it is hard to combine large detection area at high energies (which suggests a large spacing of detector elements) with a low energy threshold (which require a small spacing), one may consider the worldwide operation of several complementary detectors.

Apart from elongated tracks, *cascades* can be detected. Their length increases only like the logarithm of the cascade energy. With typically 5-10 meters length, cascades may be considered as quasi point-like compared to the spacing of photomultipliers in Cherenkov telescopes. The effective volume for cascade detection is close to the geometrical volume. While for present telescopes it therefore is much smaller than that for muon detection, for kilometer-scale detectors and not too large energies it can reach the same order of magnitude like the latter.

Ultra-high energy cascades could be detected not only by their Cherenkov light but also by coherent Cherenkov waves in the radio range or by acoustic pulses. With an attenuation length on the kilometer scale, these techniques allow detection volumes of Giga-tons or even higher. Since the initial energy has to be very high to yield a detectable signal at all, they may start to compete with optical detectors only above a few PeV.

Figure 1 sketches the detector masses and energy ranges which are characteristic for underground detectors, for optical detectors in water or ice, and for acoustic and radio detectors.

2. Optical Detectors under water and ice

Optical underwater detectors consist of a lattice of photomultipliers (PMs) spread over a large open volume in the ocean, in lakes or in ice. The PMs record arrival time and amplitude of Cherenkov light emitted by muons or cascades.

The development in this field was largely stimulated by the DUMAND project [8] which was cancelled in 1995. The other pioneering experiment is the Baikal telescope [9]. The Baikal collaboration not only was the first to deploy three strings (as necessary for full spatial reconstruction [10]), but also reported the first atmospheric neutrinos detected underwater [11]. At present, NT-200, an

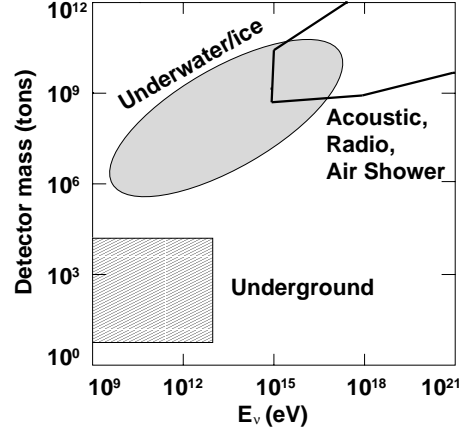


Figure 1. Domains of different detection techniques.

array comprising 192 PMs, is taking data. With respect to its size, NT-200 has been surpassed by the AMANDA detector at the South Pole [12,13]. With 677 PMs, the present AMANDA-II array reaches an area of a few 10^4 m^2 for 1 TeV muons. Although still far below the square kilometer size suggested by most theoretical models [1,3,17], AMANDA-II may be the first detector with a realistic discovery potential with respect to extraterrestrial high energy neutrinos. Limits obtained from the analysis of data taken with the three times smaller AMANDA-B10 in 1997 have been reported at this conference [13]. The limit on the diffuse flux from unresolved sources with an assumed E^{-2} spectrum is of the order of $10^{-6} E_\nu^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$, close to the recent bound established by Mannheim, Protheroe and Rachen [19] but still above the bound given by Waxmann and Bahcall [20]. The flux limit on point sources with an E^{-2} spectrum at the northern sky (declination larger than 30 degrees) is of the order of $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 10 \text{ GeV}$. The overall sensitivity of AMANDA-B10 has been verified by a sample of more than 200 events which is dominated by atmospheric neutrinos.

Two projects for large neutrino telescopes are underway in the Mediterranean - ANTARES [15] and NESTOR [14]. Both have assessed the relevant physical and optical parameters of their sites, developed deployment methods and

performed a series of operations with a few PMs. ANTARES and NESTOR envision different deployment schemes and array designs. The NESTOR group plans to deploy a tower of several floors, each carrying 14 PMTs. The ANTARES detector will consist of 13 strings, each equipped with 30 storeys and 3 PMTs per storey. This detector will have an area of about $3 \cdot 10^4 \text{ m}^2$ for 1 TeV muons - similar to AMANDA-II - and is planned to be fully deployed by the end of 2003. On top of these two advanced projects, there is an Italian initiative, NEMO [16], which studies appropriate sites for a future km^3 detector and started with *R&D* activities.

There have been longstanding discussions about the best location for future km^3 telescopes. What concerns geographic location, one detector on each hemisphere would be ideal for full sky coverage. With respect to optical properties, water detectors in oceans seem to be favored: although the absorption length of Antarctic ice at Amanda depths is nearly twice as long as in oceans (and about four times that of Baikal), ice is characterized by strong light scattering, and its optical parameters vary with depth. Light scattering leads to a considerable delay of Cherenkov photons. On the other hand ice does not suffer from the high potassium content of ocean water or from bioluminescence. These external light sources result in counting rates ranging from several tens of kHz to a few hundred kHz, compared to less than 500 Hz pure PM dark count rate in ice. Depth arguments favor oceans. Note, however, that this argument lost its initial strength after BAIKAL and AMANDA had developed reconstruction methods which effectively reject even the high background at shallow depths. What counts most, at the end, are basic technical questions like deployment, or the reliability of the single components as well as of the whole system. Systems with a non-hierarchical structure like AMANDA (where each PM has its own 2 km cable to surface) will suffer less from single point failures than water detectors do. In the case of water, longer distances between detector and shore station have to be bridged. Consequently, not every PM can get its own cable to shore, resulting in a strictly hierarchical system

architecture. This drawback of water detectors may be balanced by the fact that they allow retrieval and replacements of failed components - as the BAIKAL group has demonstrated over many years.

Most likely, the present efforts will converge to two km^3 detectors for very high energy neutrinos, one at the South Pole and one in the Mediterranean (with the Baikal site possibly filling a niche at intermediate energies). Representatively for these large telescopes, the following section sketches ICECUBE, the most advanced design for such an detector.

3. ICECUBE

The proposed ICECUBE detector consists of 4800 PMTs deployed on 80 vertical strings. It is planned to install up to 16 strings per austral summer season. Fig. 2 gives a top view of the proposed geometry and the position of the array with respect to AMANDA-II and the air shower array SPASE-2.

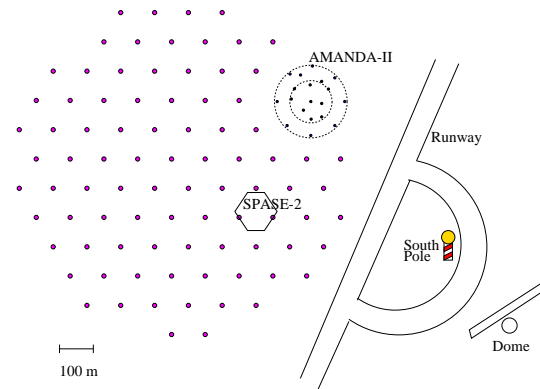


Figure 2. Top view of the proposed ICECUBE detector

The detailed geometry is still being optimized. The default geometry assumes a string spacing of 125 m and distances of PMTs along a string of 16 m. In the course of MC simulations, these parameters have been varied over a wide range. Apart from uniform arrays, also nested configurations with sub-arrays of higher density have been

simulated [22,21]. Fig.3 gives the effective area as a function of string spacing. Clearly, detection of 100 GeV muons gets worse for the large spacing preferred at energies above a TeV. Raising the number of PMTs leads to a lower energy threshold provided the side length of the detector is kept constant. On the other hand, the maximum effect for high energy muons is obtained if not only the number of PMTs but also the spacing is increased. Clearly, the final configuration is a function of physics priorities. I mention a few of them in the following.

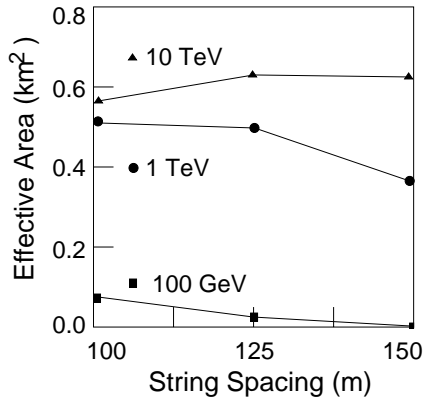


Figure 3. ICECUBE effective area at different energies as a function of string spacing

Search for extraterrestrial high energy neutrinos

ICECUBE would record about 35,000 (3,000) atmospheric neutrinos with energies of 1-10 (10-100) TeV. The number of reconstructable events below 1 TeV also reaches a few 10^4 but depends strongly on the efficiency of background rejection. An extraterrestrial diffuse flux from AGN of $10^{-7} E_\nu^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$, one order of magnitude below the theoretical bound derived in [19], would result in 600 (800) events with energies of 1-10 (10-100) TeV. Energy reconstruction is crucial to identify AGN neutrinos. With present algorithms, a resolution $\sigma(\ln E_\mu) \approx 0.4$ has been obtained (i.e. slightly better than one order of magnitude). We anticipate that this value can be improved to 0.25 with the help of

advanced methods. If the majority of the AGN neutrinos would come from a few tens of AGN, the signal-to-background ratio would be improved by up to two orders of magnitude. This would be essential for detecting an extraterrestrial excess at energies below 100 TeV.

With a pointing accuracy of about one degree or better, the easiest search strategy will be a point source analysis (see for details [13]). In this case, the atmospheric neutrino background is reduced by nearly four orders of magnitude.

Fig.4 [18] shows theoretical predictions and bounds on the diffuse flux of extraterrestrial neutrinos as well as the flux of atmospheric neutrinos. ICECUBE might search for a signal down to a few $10^{-9} E_\nu^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$.

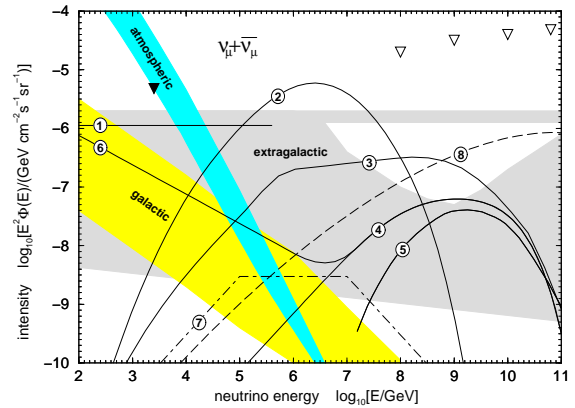


Figure 4. Summary of expected $\nu_\mu + \bar{\nu}_\mu$ intensities. Numbered lines: 1-4,6) AGN models (Nellen93, Stecker96, Mannheim et al., Mannheim 94), 5) neutrinos from interaction of UHE protons with cosmic microwave background (Protheroe96), 7) GRB model (Waxmann, Bahcall), 8) neutrinos from topological defects (Sigl98) Shaded regions: theoretical bounds on diffuse fluxes from [19]. Bold triangle: Frejus limit on excess above atmospheric neutrinos, blank triangle: limits on upward events from Fly's Eye. Figure taken from [18])

Search for magnetic monopoles

A magnetic monopole with unit magnetic Dirac charge $g = 137/2 \cdot e$ and velocities above the Cherenkov threshold in water ($\beta > 0.75$) would

emit Cherenkov radiation smoothly along its path, exceeding that of a bare relativistic muon by a factor of 8300 [23]. This is a rather unique signature. Fig.5 summarizes the limits obtained until now [24]. A cube kilometer detector could improve the sensitivity of this search by nearly two orders of magnitude. The search could be extended to even lower velocities by detecting the δ electrons generated along the monopole path.

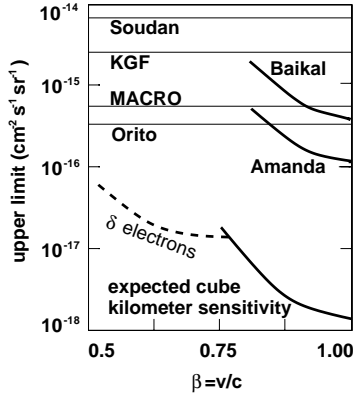


Figure 5. Limits on the flux of relativistic monopoles

Indirect WIMP search

The annihilation of neutralinos trapped within the core of the Earth or in the Sun would generate high energy neutrinos from the nearly vertical direction or from the Sun, respectively [25]. Present searches by experiments underground and underwater for an excess of muons from the center of the Earth exclude a fraction of supersymmetric models with neutralino masses above 50-100 GeV. Provided a muon detection threshold of about 20 GeV, a cube kilometer detector might complement future direct search experiments for WIMPs like CRESST or GENIUS [26].

Supernova Bursts

Due to the low external noise rate, already the present AMANDA array is sensitive to an in-

crease of the individual counting rates of all PMs resulting from a Supernova burst closer than 8-9 kpc [27,28]. ICECUBE will monitor the full Galaxy. Within a worldwide Supernova Early Warning System [6], this observation would confirm other records. If several detectors spread around the world would measure the signal front with an accuracy of a few ms, one possibly might determine the supernova direction by triangulation [29].

4. Acoustic Detection

Acoustic detection was proposed first in the fifties [30]. A particle cascade deposits energy into the medium via ionization losses, which is converted within a nanosecond into heat. The effect is a steep expansion, generating a bipolar acoustic pulse with a width of a microsecond. Transverse to the pencil-like cascade (diameter 10 cm) the radiation is coherent and propagates within a disk of about 10 m thickness (the length of the cascade) into the medium (see fig.6). The frequency peaks at 20 kHz where the attenuation length of sea water is a few kilometers, compared to a few tens of meters for light. Given a large initial signal, huge detection volumes can be achieved. The magnitude of the signal is proportional to the heat expansion coefficient and the cascade energy, Acoustic pulses from a 200 MeV beam directed into a water tank were measured in 1978 [31]. Due to the dependence on the expansion coefficient, the signal should disappear at temperatures close to 4° C. Warmer water should give a higher signal, favoring the Mediterranean with about 14° C at 4 km depth [32]. Since the signal also scales with the square of the inverse cascade diameter, details of cascade simulation are essential for the signal prediction and have been the main reason early disagreement between various authors. Following recent calculations [33], a 10 PeV cascade would generate a signal of 60 μ Pa at a distance of 400 m, which is comparable to the sensitivity of the human ear. However, the main challenge of the method is the Ocean noise background. The signal-to-noise ratio may be improved through coincident detection by many hydrophones close to each other as

well as at several strings (fig.6). Provided efficient noise rejection, acoustic detection might be competitive with optical detection at multi-PeV energies. Since recent AGN models suggest several events above 1 PeV per year and km^3 , the method is clearly worth to be pursued.

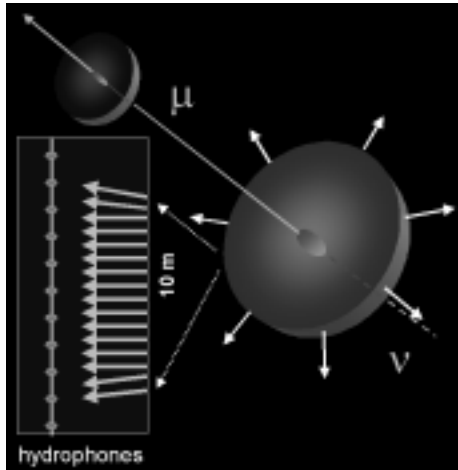


Figure 6. Principle of acoustic detection

A Russian group has been working on the development of SADCO, an acoustic array at the NESTOR site, which is planned to consist of 3 strings each instrumented with 128 hydrophones [32]. The calculated threshold is 6 PeV within a km^3 volume. Due to the priority of building an optical detector, the project is dormant at present.

The same group considers to test an existing sonar array for submarine detection close to Kamchatka. The peak sensitivity of the 2400 hydrophones, however, is only a few hundred Hz, therefore only a small fraction of the original signal is captured. Anyway the array might turn out to be useful: Given the large attenuation length at these frequencies, it may search for neutrinos with energies beyond 10^{20} eV in a volume of 100 km^3 or more.

First acoustic signals from particle cascades in

open water have possibly been identified in Lake Baikal [9]. The group operated an air shower array on the ice in coincidence with a hydrophone installed 5 meters under the ice cover, with the aim to detect the acoustic signal generated by the airshower core in water. Indeed a series of signals with the proper width of a few hundred microseconds have been detected. In order to confirm the nature of the pulses, an experiment with better noise reduction and higher redundancy will be performed in March 2001.

5. Radio Detection

Electromagnetic showers generated by high energy electron neutrino interactions emit coherent Cherenkov radiation [34]. Electrons are swept into the developing shower, which acquires a negative net charge. This charge propagates like a relativistic pancake of 1 cm thickness and 10 cm diameter. Each particle emits Cherenkov radiation, with the total signal being the resultant of the overlapping Cherenkov cones. For wavelengths larger than the cascade diameter, coherence is observed and the signal rises proportional to E^2 , making the method attractive for high energy cascades. The bipolar radio pulse has a width of 1-2 ns. In ice, attenuation lengths of several kilometers can be obtained, depending on the frequency band and the temperature of the ice. Thus, for energies above a few PeV, radio detection in ice promises to be superior to optical detection [35,36].

First studies with respect to noise temperature have been performed at the Russian Vostok station in Antarctica [37]. Meanwhile, a prototype Cherenkov radio detector called RICE is operated at the geographical South Pole. Twenty receivers and emitters are buried at depths between 120 and 300 m (see fig.7). Analog signals are read out via coaxial cable, limiting the bandwidth and therefore the fraction of the GHz signal arriving at the surface. The use of optical cables would allow to go deeper in order to reduce noise from the surface and to get better conditions for coincident operation with AMANDA. The data analyzed at present show that radio sources can be reconstructed with about 10 m accuracy. From the

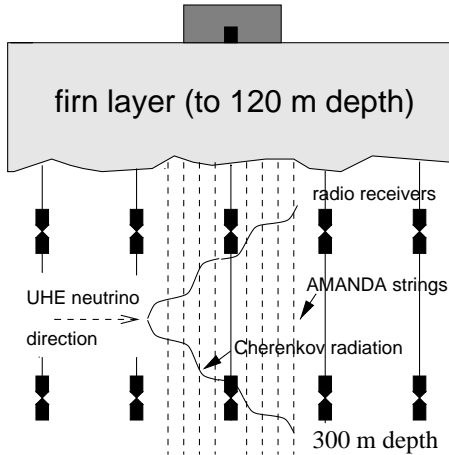


Figure 7. Schematic view of the RICE array at the South Pole

non-observation of very large pulses, first physically relevant upper limits for energies above 100 PeV are going to be derived [38].

6. Megaton detectors with low threshold

A future cube kilometer detector will be optimized to energies at or above 1 TeV rather than to the low energy range typical for oscillations and WIMP search. There is, however, much motivation to build Megaton detectors with a lower threshold.

One proposal suggests an underground water-Cherenkov detector like Super-Kamiokande, but with fiducial volume of 650 ktons [39]. The detection threshold of about 7 MeV would allow to cover a wide range of physics questions, like solar neutrinos, proton decay, search for Supernova bursts, neutrino oscillations in the GeV range and search for WIMPs. Other schemes proposed employ the ring imaging technique [40,41], with an ultimate size of one Megaton and a similar range of physics goals.

An underwater detector with several Megatons geometrical volume and with a threshold of about 5 GeV could bridge the gap between the low threshold underground detectors and cube kilo-

meter arrays. It would have a better sensitivity to neutrinos from WIMP annihilations than underground detectors and might do astrophysics searches in a range complementary to the large arrays. Such an detector could be build at the Baikal site or as a sub-detector nested in one of the large arrays.

7. Detection at Ultra-High energies

Radio and acoustic detection may take over from the optical Cherenkov methods at energies above 10 PeV. However, with the exception of the proposed method to use sonar submarine detection techniques for detection of 10^{20} eV neutrinos, these methods run out of rate for energies in the EeV range (10^{18} eV).

At higher energies, a large extensive air shower (EAS) array like AUGER may seek for horizontal air showers due to neutrino interactions deep in the atmosphere. The optimum sensitivity window is between 10^{18} and 10^{20} eV. Given an effective detector mass between 1 and 20 Giga-tons, the estimated sensitivity is about $10^{-7} E_\nu^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$.

Heading to higher energies leads to space based detectors monitoring larger volumes than visible from any point on the Earth surface. The EUSO (formerly OWL-Airwatch) project [43] foresees to launch large mirrors with optical detectors to 500 km height. The detector would look down upon the atmosphere and search for nitrogen fluorescence signals due to neutrino interactions. The monitored mass would be up to 10 Tera-tons, with an energy threshold of about 10^{19} GeV.

I finally mention an experiment having searched for radio emission from extremely-high energy cascades induced by neutrinos or cosmic rays in the lunar regolith [44]. Using two NASA antennas, within 12 hours effective data taking an upper limit of $E_\nu^2 \cdot dN/dE < 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$ at 10^{20} eV, has been obtained, close to predictions from topological defect models.

8. Conclusions

After a long period of development, the first optical underwater/ice Cherenkov detectors,

BAIKAL and AMANDA, have detected neutrinos, with effective areas in the range of 10^3 to 10^4 m². Mediterranean detectors are expected to follow soon. However, in order to prove most "realistic" models on neutrino production by AGN or GRB, one needs kilometer scale detectors. This scale is also suggested by the pretention to open a really new window - i.e. to increase the sensitivity compared to existing devices by 2-3 orders of magnitude. This is a scale which historically nearly inevitably has led to unexpected discoveries. Physics as well as economic arguments suggest one km³ detector on each hemisphere.

Optical detectors may see only the low energy part of interesting phenomena. Therefore further development and funding for acoustic as well as radio detection is substantial. These techniques should be tested hand in hand with the construction of the big optical arrays.

On the low energy side, Mega-ton detectors with threshold of a few GeV or lower could continue the physics program typical for present underground detectors with higher sensitivity and complement the TeV program of the large arrays by searches in the range below 100 GeV.

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